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Frequency domain mediolateral balance assessment using a center of pressure tracking task

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ABSTRACT

Since impaired mediolateral balance can increase fall risk, especially in the elderly, its quantification and training might be a powerful preventive tool. We propose a visual tracking task (VTT) with increasing frequencies (.3–2.0 Hz) and with center of pressure as visual feedback as an assessment method. This mediolateral balance assessment (MELBA) consists of two tasks, tracking a predictable target signal to determine physical capacity and tracking an unpredictable target signal to determine sensorimotor integration limitations. Within and between sessions learning effects and reliability in balance performance descriptors in both tasks were studied in 20 young adults. Balance performance was expressed as the phase-shift (PS) and gain (G) between the target and CoP in the frequency domain and cut-off frequencies at which the performance dropped. Results showed significant differences between the MELBA tasks in PS and G indicating a lower delay and higher accuracy in tracking the predictable target. Significant within and between sessions learning effects for the same measures were found only for the unpredictable task. Reliability of the cut-off frequencies at which PS and G performance declined and the average values within cut-off frequencies was fair to good (ICC .46–.66) for the unpredictable task and fair to excellent for the predictable task (ICC .68–.87). In conclusion, MELBA can reliably quantify balance performance using a predictable VTT. Additionally, the unpredictable tasks can give insight into the visuomotor integration mechanisms controlling balance and highlights MELBA's potential as a training tool.

1. Introduction

Balance impairments are a common cause of falls in the elderly population (Maki et al., 1994; Muir et al., 2010; Salzman, 2010). Detriments of the somatosensory and neuromuscular systems have been identified as causes of imbalance when standing and walking in the elderly (Horak, 2006; Lord et al., 2003, 1999, 2007; Lord and Ward, 1994; Orr, 2010; Orr et al., 2006; Salzman, 2010). The inability to adequately integrate sensory inputs as well as difficulties to perform dual-tasks in which cognition is required have also been identified as causes of balance impairments in older adults (Hay et al., 1996; Maki and McIlroy, 2007; Maki et al., 2001; ShumwayCook et al., 1997). Previous investigations have demonstrated that several biomechanical variables of balance control in the medio-lateral (ML) direction can identify fallers when standing (i.e. ML postural sway measures) and when inducing sideward stepping responses (Brauer et al., 2000; Hilliard et al., 2008; Lord et al., 1999; Maki et al., 1994; Melzer et al., 2010; Williams et al., 1997). There are also indications that center of mass displacement (CoM) in the frontal plane, when compared to sagittal, requires greater active control when walking (Bauby and Kuo, 2000; Donelan et al., 2004; O'Connor and Kuo, 2009). Furthermore, evidence has shown that balance training targeting movements in the frontal plane may reduce the incidence of falls in community-dwelling elderly people (Hatzitaki et al., 2009; Waddell et al., 2009; Yungher et al., 2012).

Despite the discriminative capacity (fallers from non-fallers) of ML balance control reported in retrospective studies, only two of the biomechanical variables (i.e., spontaneous sway of the center of pressure (CoP) during quiet standing and gluteus medius onset time in a stepping response task) have shown poor to moderate accuracy in prospectively predicting falls (Brauer et al., 2000; Maki et al., 1994). It is possible that due to a ceiling effect of current balance assessment tools, including clinical measures, those tests

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are not sensitive enough to detect balance impairments and predict falls in high functioning elderly and in able-bodied subjects (Bhatt et al., 2011; Brauer et al., 2000; Faber et al., 2006; Muir et al., 2010; Pardasaney et al., 2012). Therefore, a more sensitive assessment method should challenge balance more to avoid ceiling effects and yet be simple enough to be applied in a clinical environment (Pardasaney et al., 2012; Woollacott, 2000). In this context, we propose a medio-lateral balance assessment (MELBA) method, which uses a visual tracking task (VTT) and the ML CoP displacement as feedback on performance.

In the VTT subjects have to elicit voluntary ML CoP movements based on visual information of the target and subordinating proprioceptive and vestibular sub-systems to maintain stability. By increasing task difficulty (i.e. increasing target frequencies), the subject is challenged to respond fast and accurately. These aspects of the response are necessary when coping with perturbations in daily life situations and reflect the integrity and compensatory ability of the balance system. MELBA aims to quantify balance performance using a visual tracking task, whereby balance control is then characterized by gain and phase-shift between target and CoP signals. MELBA consists of a predictable target, which allows feed-forward mechanisms to control balance in order to determine maximal physical capacities, and a second, unpredictable target, which increases the demand of feedback mechanisms in order to quantify limitations in sensory integration.

This study aimed to determine the methodological properties of MELBA by assessing learning effects within and between sessions as well as reliability of the performance, i.e. the consistency of the method when no interventions are made. Additionally, balance performance between the two MELBA tasks (i.e., predictable versus unpredictable) was compared.

2. Methods

2.1. Subjects

Twenty healthy young adults, 12 women and 8 men, participated in this study (age: 28 ± 3 years; height: $1.75 \pm .1$ m; weight: 70 ± 8 kg). Participants did not report any musculoskeletal or neurological condition that may have affected balance. This research was approved by the local Ethical Committee, in accordance with the ethical standards of the declaration of Helsinki. All subjects were informed of the experimental procedures and signed an informed consent form prior to the experiment.

2.2. Task and procedure

Each participant performed a series of visual tracking tasks (VTT) while standing barefoot and with the arms crossed on a force-plate located in a quiet and low-intensity light room (for set-up details see Fig. 1). CoP data were obtained using a Kistler-9281B force plate (Kistler Instruments AG, Winterthur, Switzerland) sampling at 60 samples/s. D-flow 3.10.0 software (Motek Medical, The Netherlands) was used to produce target signals as well as to record and display target and CoP data on the screen. The delay of the system was calculated to be 16 ms which is equivalent to 1 sample.

A *predictable* target signal was constructed using 18 blocks of 5 s, each composed by one sine wave, which increased from .3 to 2.0 Hz in steps of .1 Hz. This information was enhanced using a metronome synchronized with the maximum displacement of the target in order to increase sensory input abundance. The total task time was 90 s.

An *unpredictable* target signal was constructed using 15 blocks composed by the sum of 6 consecutive sine waves separated by .1 Hz. A pseudorandom phase-shift between sine waves between −1 and 1 periods was introduced in order to avoid predictability. After each block the lowest frequency, which started at .1 Hz was increased by .1 Hz higher until it reached 1.5 Hz. Duration was 10 s for blocks 1 and 2, 8 s for blocks 3 to 7, 6 s for blocks 8 to 11 and 4 s for blocks 12 to 15. Duration of the blocks was chosen in order to obtain at minimum of 2 cycles per frequency contained in the block. This target construction also allowed limiting the total task time to 100 s. The unpredictable target bandwidth started at a lower frequency than the predictable target, but results in the frequency range .1–.2 Hz were not analyzed. An example of the two target signals is depicted in Fig. 1.

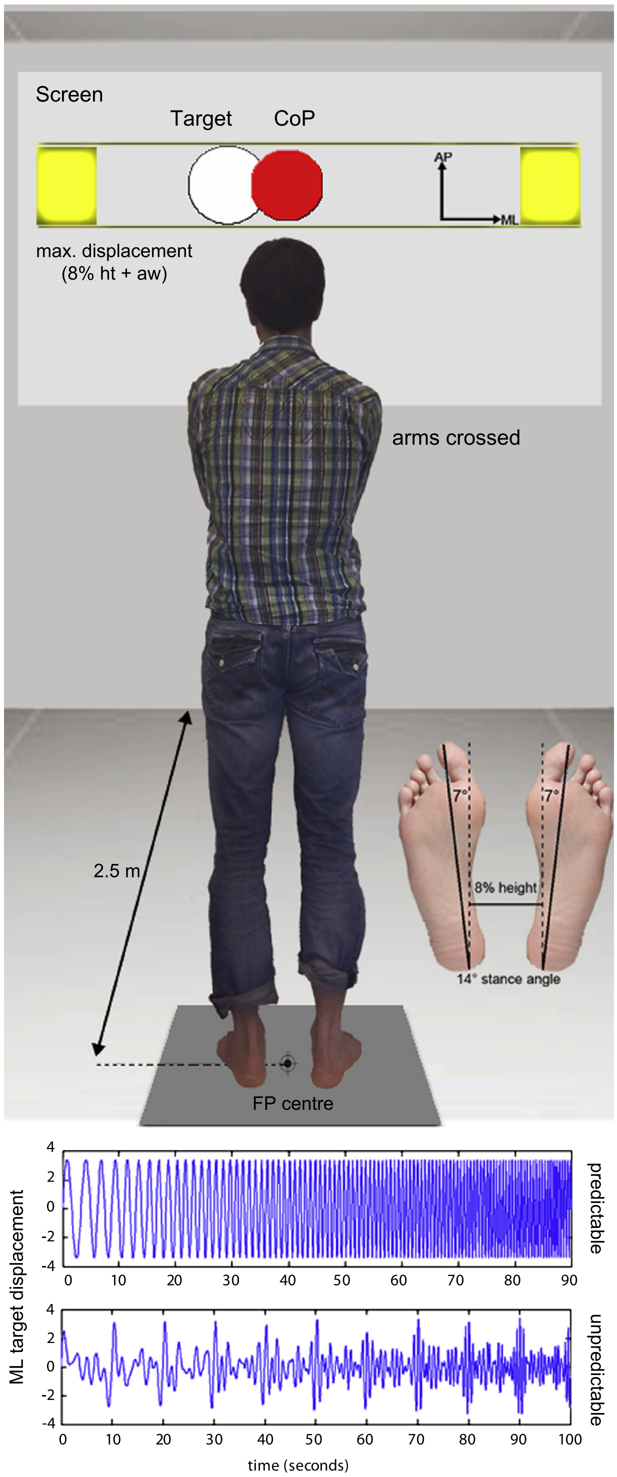

Fig. 1. Illustration of the experimental set-up from a rear view. The CoP (center of pressure) is represented as red sphere, whereas a white sphere represents the target signal, on a display located 2.5 m in front of the forceplate (FP). The height (ht) and ankle width (aw) were used to determine the maximum amplitude of the target indicated by the yellow areas projected at both sides of a corridor delimited by a top and bottom horizontal bars. These bars indicate the tolerance for anterior–posterior (AP) displacement which was set at 2 cm. Additional auditory feedback ("beep") was given when these AP boundaries were exceeded. The figure of feel soles inserted at the right depicts foot positioning across all trials (7° rotation of each foot with an intermalleoli distance equal to 8% of ht). The lower panel depicts the predictable (top) and unpredictable (bottom) targets. Negative and positive values indicate left and right CoP displacements, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The VTT consisted of tracking the predictable or unpredictable target signal using the ML displacement of the CoP projected on a screen in front of the subject. The screen (2×1.5 m^2 size) was placed 2.5 m in front of the force plate center. The target signal and CoP were represented by white and red spheres of 11 and 9 cm diameter, respectively. Each participant performed 8 VTT trials: 4 with the predictable and 4 with the unpredictable target. Before performing the tasks two practice trials were allowed for each of the conditions. This session was repeated 7 days later at the same time of the day in order to avoid the influence of the circadian cycle in the variables measured (Swanenburg et al., 2008). Trials were performed with at least with 1 minute rest in between. Since stance width alters lower limb neuromechanical responses when displacing CoM and CoP in the ML direction (Bingham et al., 2011; Henry et al., 2001), stance width was standardized by setting the intermalleoli distance to 8% of body height. A fixed 14° stance angle was used across all participants (Fig. 1). These stance measures have been shown to be within the values of normal stance (McIlroy and Maki, 1997). Target maximum side-to-side displacement for both target signals was normalized for each subject at stance width plus ankle width; allowing CoP ML displacements to be within the BoS. On average, participants stood on the force plate with $14 \pm .8$ cm distance between malleolus or stance width, being $7.1 \pm .6$ cm the average ankle width which determined a maximum target displacement of 21.1 ± 1.3 cm. The projected maximum target displacement was 1.4 m side-to-side, therefore the gain factor for CoP displacements projected on the screen ranged from 6.0 to 7.5 with an average of $6.7 \pm \pm .4$.

Anterior–posterior displacements of the CoP were constrained by allowing only 3.2 cm fore-aft displacement around the CoP at rest, which was indicated by the projection of two yellow bars above and below the target signal. The computer produced an auditory cue whenever CoP movement exceeded these constraints.

2.3. Data analysis

All data analysis was performed using custom-made software in Matlab R2011a (Mathworks, Natick MA, USA). Balance performance over the frequency ranges in the target signal was described by gain, and phase-shift of the linear constant coefficient transfer function between CoP and target signal. This analysis was performed using the Welch algorithm over windows of .25 times the length of the target (per block) with 90% overlap between windows, with zero-padding as required to obtain .1 Hz resolution. For each block we maintained estimates of gain and phase-shift only for the frequencies present in the target presented in that block. The results for all blocks of one trial were combined after estimation of the transfer functions, to obtain gain and phase-shift values at all frequencies presented. For the unpredictable target, phase-shift, gain and coherence were calculated as the average of the values at each frequency over blocks with overlapping frequency content. The phase-shift (PS) reflects the delay (in degrees) between target and CoP at each frequency, whereas gain (G) reflects the ratio between the target and CoP amplitudes; both in the frequency domain. Perfect performance implies PS=0 and G=1. In addition, the coherence (Coh) was determined, as a measure of linear correlation between the target and CoP in the frequency domain, which in this study was used to corroborate the assumption of input (target)/output (CoP) linearity and therewith the validity of estimates of PS and G. Considering that each coherence estimate was determined from 16 independent data windows (4 windows per block times 4 trials), the threshold for significance of coherence can be estimated at .181 (Amjad et al., 1997; Shumway and Stoffer, 2000). To characterize balance performance, 4 descriptors were calculated. First, the average of the three highest values for each measure in each trial was calculated and the values at which PS and G dropped below 75% of this average were determined as the cutoff frequencies (coined PSX and GX). Second, PSY and GY were computed as the average of the G and PS values within the bandwidth determined by PSX and GX, respectively. For better clarity, calculations of performance descriptors are illustrated in Fig. 2.

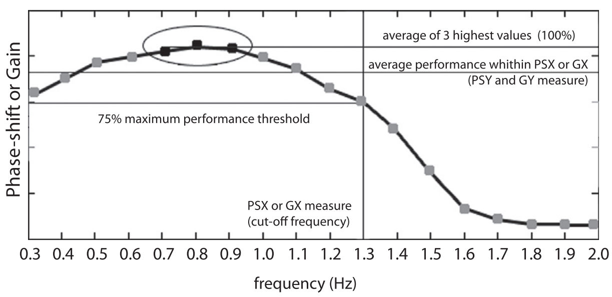

Fig. 2. Figure illustrates the calculation of performance descriptors. First, the three highest values for G and PS were indentified (circled black dots) and averaged. Second, 75% of the previously calculated mean was used as performance threshold for G and PS. The frequency (Hz) of last values above this threshold was used as cutoff frequency for PSX and GX, respectively (vertical dashed line). Finally, the averages of the PS and G values within PSX and GX, (PSY and GY, respectively) characterized performance within the cutoff frequency (horizontal line).

2.4. Statistical analysis

To test for learning effects, repeated measures ANOVAs were performed on the average of phase-shift and gain over all frequencies and for the dependent measures PSX, GX, PSY and GY using 2 (predictable and unpredictable target) $\times$ 2 (assessment day) $\times$ 4 (trial number) models.

In view of multiple testing, α was Bonferroni corrected at .0083 (.05/6). To determine between-days reliability of performance descriptors, further analysis included intraclass correlations (ICC 2,1) for absolute agreement by using descriptors averaged within assessment days. Measures were considered to exhibit excellent reliability when ICC > .75 and fair to good reliability when ICC value was between .4 and .75 (Fleiss, 1986). Assumption of normality of the data was confirmed by Shapiro–Wilks tests. Statistical analyses were performed using SPSS (PASW statistics 18) and Matlab.

3. Results

Participants did not report fatigue during or after the trials and were able to complete all trials. Fig. 3 illustrates average performance over subjects when tracking both targets. Descriptive statistics and repeated measures ANOVAs for the measures of PS and G are summarized in Table 1.

Average values for Coh for the predictable target were .88 and .89, whereas for the unpredictable target these were .45 and .52 for sessions 1 and 2, respectively. These values were high above chance levels indications that the relation between the CoP and the predictable target was sufficiently strong and linear to allow estimation of transfer functions between target and CoP signals.

Overall, a significant main effect was found for target (Table 1), indicating that participants exhibited better mediolateral balance performance (PS, G) when tracking the predictable target compared to the unpredictable target (Fig. 2). On average, when tracking the predictable target, participants performed nearly in-phase (PS $\approx$ 0) and close to optimal (G $\approx$ 1) for input frequencies below 1.2 Hz. For the unpredictable target, near-optimal performance values for PS and G were only observed during the second session in between .4 and 1.0 Hz.

Cut-off frequencies for PS and G (PSX and GX, respectively) were significantly higher when tracking the predictable target compared to the unpredictable target as indicated by a main effect of target on these parameters (Table 1 and Fig. 2). A similar effect was observed for PSY (greater PS) and GY (higher G). The between sessions effect was significant for PSX and PSY showing a learning effect after one week, whereas this learning effect was not statistically significant for GX and GY. A main effect of trial was observed only for PSY showing that significant differences were not coupled with changes in the cutoff frequency within a session. Compared to the predictable target, PSY was found to increase significantly more during the second day for the unpredictable target (target $\times$ day interaction). Compared to the predictable target, and the first assessment, no significant differences were found among trials (target $\times$ trial and day $\times$ trial interactions) for the performance descriptors. All factors interactions were also not significant.

Further analysis of reliability of the performance descriptors showed that for the predictable task, these measures were good (PSY=.68, GX=.72, GY =.71) to excellently reliable (PSX=.87). When using the unpredictable target, reliability was good (PSX=.64, PSY=.46, GX=.49 and GY=.66).

4. Discussion

This study explored learning effects within and between sessions and reliability of mediolateral balance performance descriptors when using visual tracking tasks based on center of pressure feedback; for both a predictable and an unpredictable target. Linearity between ML

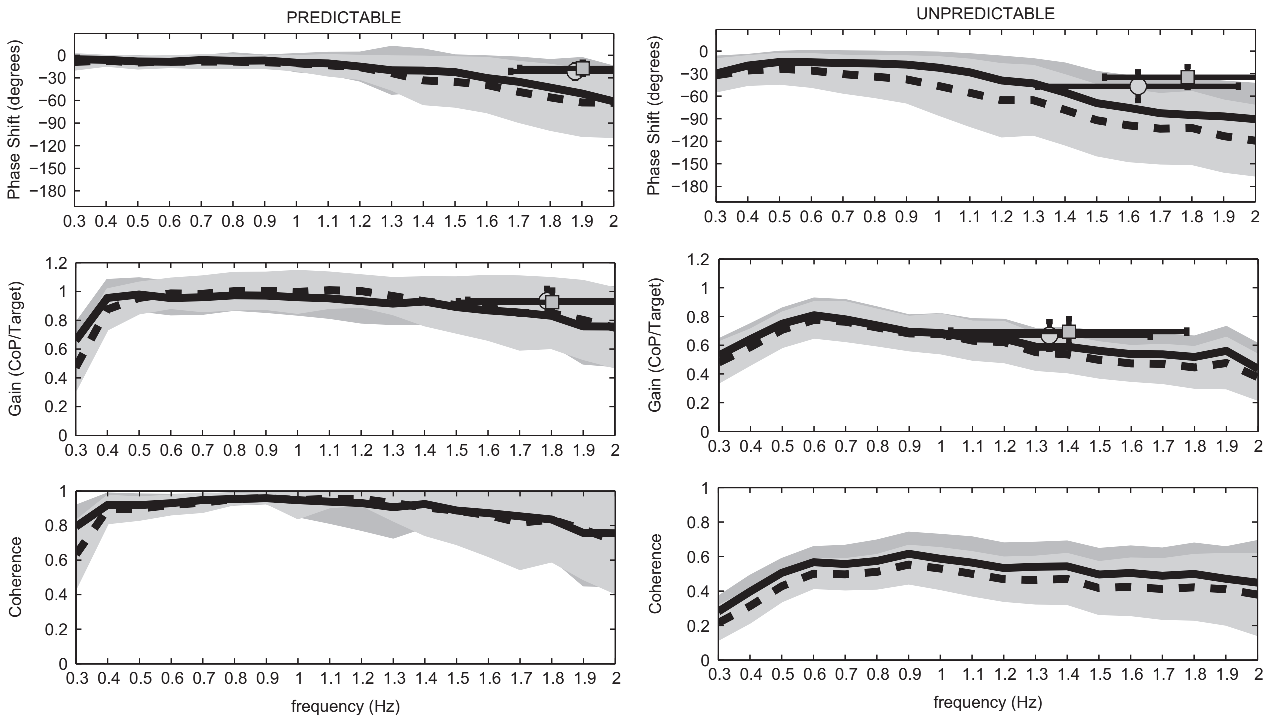

Fig. 3. Averaged curves (±sd) for phase shift (top panel), gain (mid panel) and coherence (bottom panel) measures for the predictable target (left) and unpredictable (right) targets, during first (dashed line) and second (continuous line) sessions. Gray shading indicates the ±sd for all subjects and for all trials. Crosses inserted in the plots indicate means (±sd) for performance descriptors for the first session (circular markers) and second session (square markers).

Table 1
Descriptive statistics for Phase shift, Gain and performance descriptors (PSX, PSY, GX and GY) for the predictable and unpredictable targets at both assessment days. Right part of the table summarizes the p-values of the repeated measures ANOVAs for the main factors target (unpredictable and predictable), day (initial assessment and assessment seven days later), and trial (trials 1 to 4) and all interactions effects. Statistically significant *p*-values are presented in bold.

	PREDICTABLE				**UNPREDICTABLE**				***p*-values**						
	Day 1		**Day 2**		**Day 1**		**Day 2**		**Target**	**Day**	**Trial**	**Target × Day**	**Target × Trial**	**Day × Trial**	**Target × Day × Trial**
	m	**sd**	**m**	**sd**	**m**	**sd**	**m**	**sd**							
Phase shift	−22.35	18.33	−18.33	15.47	−59.59	32.09	−40.11	26.36	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	.352	.549
PSX (Hz)	1.89	.18	1.90	.22	1.67	.32	1.82	.25	**<.001**	**.004**	.706	.013	.205	.777	.866
PSY (°)	−18.9	8.59	−14.9	8.02	−44.1	19.5	−31.5	13.8	**<.001**	**<.001**	.320	**.004**	.617	.895	.926
Gain	.90	.13	.89	.09	.59	.12	.63	.10	**<.001**	**<.001**	**<.001**	**<.001**	.055	.009	.054
GX (Hz)	1.79	.25	1.80	.30	1.34	.32	1.41	.37	**<.001**	.088	.313	.190	.327	.945	.999
GY	.93	.09	.93	.08	.67	.10	.70	.09	**<.001**	.480	.692	.970	.955	.812	.822

CoP and the target displacement was assessed using Coh measures. This measure showed a moderate to high linearity for the unpredictable and predictable VTTs, respectively, which allowed characterizing balance control with PS and G. Comparisons between MELBA tasks showed greater PS and higher G when tracking a predictable target. Significant learning effects for PS (greater PS) and G (greater amplitude) between sessions (target × day interaction) and for PS within session (target × trial interaction) for G were observed when tracking an unpredictable target. Tracking accuracy and performance improvements were also significantly reflected in some of the performance descriptors (PSX and PSY), which, nevertheless, exhibited fair to good reliability. Lower reliability of the descriptors when using the unpredictable target can be explained by the significant learning effects observed in the PS and G measures.

Overall and for both targets (predictable and unpredictable), PS and G measures declined with increasing frequency content. This demonstrates that despite the simplicity of the task, it is challenging enough to observe a decline of the mediolateral balance performance in young healthy subjects, quantified by the cut-off frequencies (PSX and GX). This suggest the potential of MELBA as a balance assessment method in community-dwelling older adults and able-bodied population, since it is not likely to suffer from ceiling effects as observed with most of the currently available tools (Muir et al., 2010; Pardasaney et al., 2012).

The first part of the MELBA test, with a predictable target, allowed assessment of physical tracking capacities, as the complexity of the task was minimized by using predictable traces and timing of the target signal and including an auditory cue (sensory redundancy). It is probable that, due to the predictable nature of this task, reliance upon feedforward control for guiding the task is increased whereas feedback control remains in place for sensing outcomes of the motor commands executed. As performance was similar over sessions for this specific task, and its descriptors (PSX, PSY, GX and GY) exhibited a fair to excellent reliability, this task seems a good measure of physical capacity: the capability to control ML balance without strong dependence on reactive control to sensory inputs, which would be more challenged by the unpredictable target.

When tracking the unpredictable target, reliance on feedback control of balance is expected to be predominant which may also account for lower performance in this task compared to the predictable target (Peterka, 2002; Peterka and Loughlin, 2004). For instance, the continuous visual inputs processing induce a visuomotor delay, which may be responsible for a larger PS, compared to the predictable target. Gain decreases, on the other hand, may be the result of amplitude scaling in order to compensate for PS increases. Therefore comparatively lower PS and *G* demonstrate that despite physical resources to control balance are available, as shown when tracking the predictable target, visuomotor delay may constrain its utilization. This highlights the importance of cognition when producing motor commands to track an unpredictable target (Maki and McIlroy, 2007).

MELBA utilized visual tracking to assess balance by triggering voluntary balance responses when dealing with a constantly changing visual stimulus, especially for the unpredictable target. However, significant within (trial effect) and between sessions (day effect) learning effects using this target were found. Some available video games use CoP displacements as means to control the game. Such videogame-based interventions can engage elderly in balance training and improve the compliance towards their rehabilitation or prevention program (Smith et al., 2011). Moreover, balance and fall risk assessment based on virtual reality environments or video games have shown to be valid and to discriminate between fallers and non-fallers (Smith et al., 2011; Yamada et al., 2011). However, most of the measures used are related to functional scores and do not give insight in the underlying mechanisms. MELBA can provide a more objective measure of the balance performance by measuring phase-shift and gain in the frequency domain.

There are some limitations that need to be addressed. First, standing position and target displacements were normalized to body height and ankle width with pelvis and hip widths not considered in the model which may have affected performance (Bingham et al., 2011; Goodworth and Peterka, 2010; McIlroy and Maki, 1997). For example, when dealing with ground ML perturbations, hip torque is lower at wide compared to narrow stance for a similar CoM displacement which requires adjustment of neural feedback gains (Bingham et al., 2011). This may affect performance when assessing older adults whom it is known to exhibit a wider stance (McIlroy and Maki, 1997). Another limitation is that participants may have implemented different strategies to track the target. We chose to provide feedback of CoP given its ease of use. While subjects were explicitly instructed to maintain body alignment, which would impose a direct relationship between CoP and body center of mass (CoM) trajectories, failure to comply with this instruction may have affected task difficulty when CoM displacements were minimized for a given CoP displacement. Especially at higher frequencies, the variability of PS and G within and across participants increased. This might reflect such changes in movement strategy with increasing frequencies. Further study will explore this CoM/CoP relationship when tracking at a range of frequencies and its effect o performance as measured with MELBA. However, preliminary data not presented in the current paper show that in fact, CoM and CoP do relate in this tracking task. However, and as is to be expected, as frequency increases CoM displacement is reduced yet remains coherent with CoP movement.

Current validation of commercially available force sensors (i.e. video game forceplate controllers) for clinical assessment may introduce opportunities for making MELBA a clinical tool (Huurnink et al., 2013). The data processing as well as interpretation could be obtained from a simplified version of the software utilized in this experiment which can be easily installed in any computer. We are currently collecting data from older adults in order to determine reference parameters from healthy older adult population. Summarizing, MELBA has potential as a ML balance assessment method and training tool. The predictable target (and its descriptors) offers insight in the maximal physical capacity of the balance system to deal with the tracking task whereas the unpredictable target can provide information on the underlying cognitive mechanisms and sensory integration for controlling balance. In addition, learning effects found when using the unpredictable target indicate that balance performance can be improved. Further studies are needed to explore the use of MELBA to quantify the effect of ageing in ML balance performance, its sensitivity to sensory manipulations, underlying tracking mechanisms, discriminative capacity between people with and without balance problems, correlation with history of falls and clinical relevance as an assessment method and training tool.

5. Conclusions

Performance in tracking a predictable target with the CoP was higher compared to tracking an unpredictable target. This may indicate higher reliance upon cognitive mechanisms for the unpredictable target, which causes a smaller phase-shift and lower gain. Performance measures in tracking a predictable target may be useful to assess maximal physical capacities on the mediolateral balance task. Performance descriptors derived from the linear transfer function between target and CoP signals provide fair to excellently reliable descriptors of balance control. Learning effects observed when using the unpredictable target may indicate MELBA's potential as a balance training tool.

Conflict of interest statement

The authors of this paper declare that no financial and personal relationships with other people or organizations have inappropriately influenced the content of the work reported in this paper.

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